

## Non-Nuclear Testing of Compact Reactor Technologies at NASA MSFC

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### INTRODUCTION

Safe, reliable, compact, autonomous, long-life fission systems have numerous potential applications, both terrestrially and in space. Technologies and facilities developed in support of these systems could be useful to a variety of concepts.

At moderate power levels, fission systems can be designed to operate for decades without the need for refueling. In addition, fast neutron damage to cladding and structural materials can be maintained at an acceptable level. Nuclear design codes have advanced to the stage where high confidence in the behavior and performance of a system can be achieved prior to initial testing.

To help ensure reactor affordability, an optimal strategy must be devised for development and qualification. That strategy typically involves a combination of non-nuclear and nuclear testing. Non-nuclear testing is particularly useful for concepts in which nuclear operating characteristics are well understood and nuclear effects such as burnup and radiation damage are not likely to be significant.

Working closely with NASA Glenn Research Center (GRC) and the Department of Energy, NASA's Marshall Space Flight Center (MSFC) has completed significant testing related to compact reactor technologies.

### SPACE FISSION POWER SYSTEM (SFPS) TECHNOLOGY

To be mass efficient, a SFPS must operate at higher coolant temperatures and use different types of power conversion than typical terrestrial reactors. The primary reason is the difficulty in rejecting excess heat to space. Although many options exist, NASA's current reference SFPS uses a fast spectrum, pumped-NaK cooled reactor coupled to a Stirling power conversion subsystem. The reference system uses technology with significant terrestrial heritage while still providing excellent performance. In addition, technologies from the SFPS system could be applicable to compact terrestrial systems.

Recent non-nuclear testing at NASA's Early Flight Fission Test Facility (EFF-TF) has helped assess the viability of the reference SFPS and evaluate methods for system integration. In July, 2011 an Annular Linear

Induction Pump (ALIP) provided by Idaho National Laboratory was tested at the EFF-TF to assess performance and verify suitability for use in a 10 kWe technology demonstration unit (TDU). In November, 2011 testing of a 37-pin core simulator (designed in conjunction with Los Alamos National Laboratory) for use with the TDU will occur. Previous testing at the EFF-TF has included the thermal and mechanical coupling of a pumped NaK loop to Stirling engines (provided by GRC). Testing related to heat pipe cooled systems, gas cooled systems, heat exchangers, and other technologies has also been performed. Integrated TDU testing will begin at GRC in 2013.

A photograph of a typical EFF-TF pumped NaK test loop is shown in Figure 1. A description of the SFPS TDU is provided in [1].

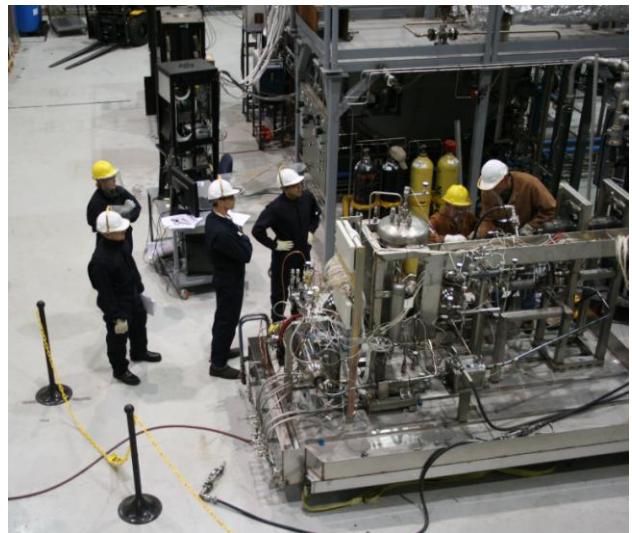


Fig. 1. Representative EFF-TF pumped NaK loop.

### THERMAL SIMULATORS

Thermal simulators developed at the EFF-TF are capable of operating over the temperature and power range typically of interest to compact reactors. Small and large diameter simulators have been developed, and simulators (coupled with the facility) are able to closely match the axial and radial power profile of all potential systems of interest. A photograph of the TDU core simulator during assembly is provided in Figure 2.



Fig. 2. Non-Nuclear Core Simulator for use with TDU.

## RESULTS

Testing to date has yielded valuable insight related to compact reactor technologies. Additional details will be provided in the presentation.

## REFERENCES

1. L. Mason, et al. "Design and Test Plans for a Non-Nuclear Fission Power System Technology Demonstration Unit" *Proceedings of Nuclear and Emerging Technologies for Space 2011*, Paper 3327, Albuquerque, NM (2011).



# **Non-Nuclear Testing of Compact Reactor Technologies at NASA MSFC**

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NASA MSFC

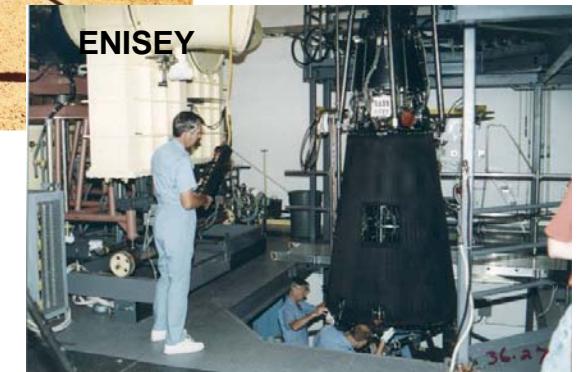
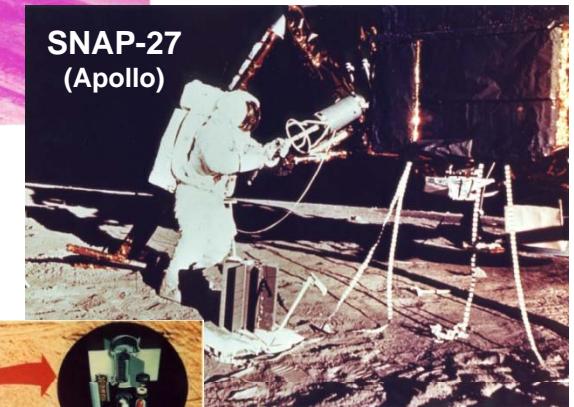
**In partnership with:**

Glenn Research Center  
Idaho National Laboratory  
Los Alamos National Laboratory  
Oak Ridge National Laboratory  
Sandia National Laboratories



# Space Nuclear Power

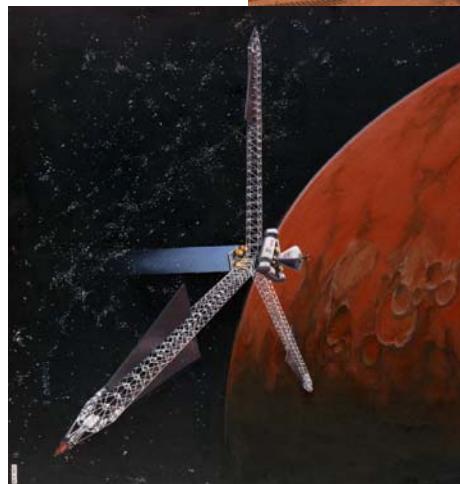
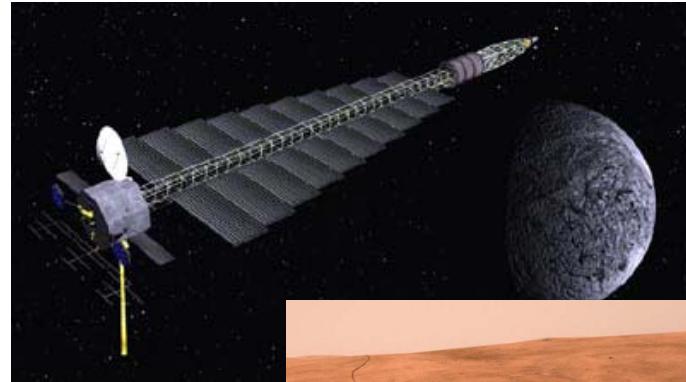
- Radioisotope Power Systems
  - 44 Successful U.S. Radioisotope Thermoelectric Generators (RTG) Flown Since 1961
  - Some Examples:
    - » Apollo SNAP-27 (1969-72)
    - » Viking SNAP-19 (1975)
    - » Voyager MHW-RTG (1977)
    - » Galileo GPHS-RTG (1989)
    - » Ulysses GPHS-RTG (1990)
    - » Cassini GPHS-RTG (1997)
    - » New Horizons GPHS-RTG (2005)
- Fission Reactor Systems
  - SNAP-10A (launched 1965)
  - Soviet Buk and Topaz (over 30 systems launched from 1967-1988)
  - SP-100 (1984-1993)
  - Jupiter Icy Moons Orbiter (2002-2005)
  - Fission Power Systems (present)





# Why Space Fission Power?

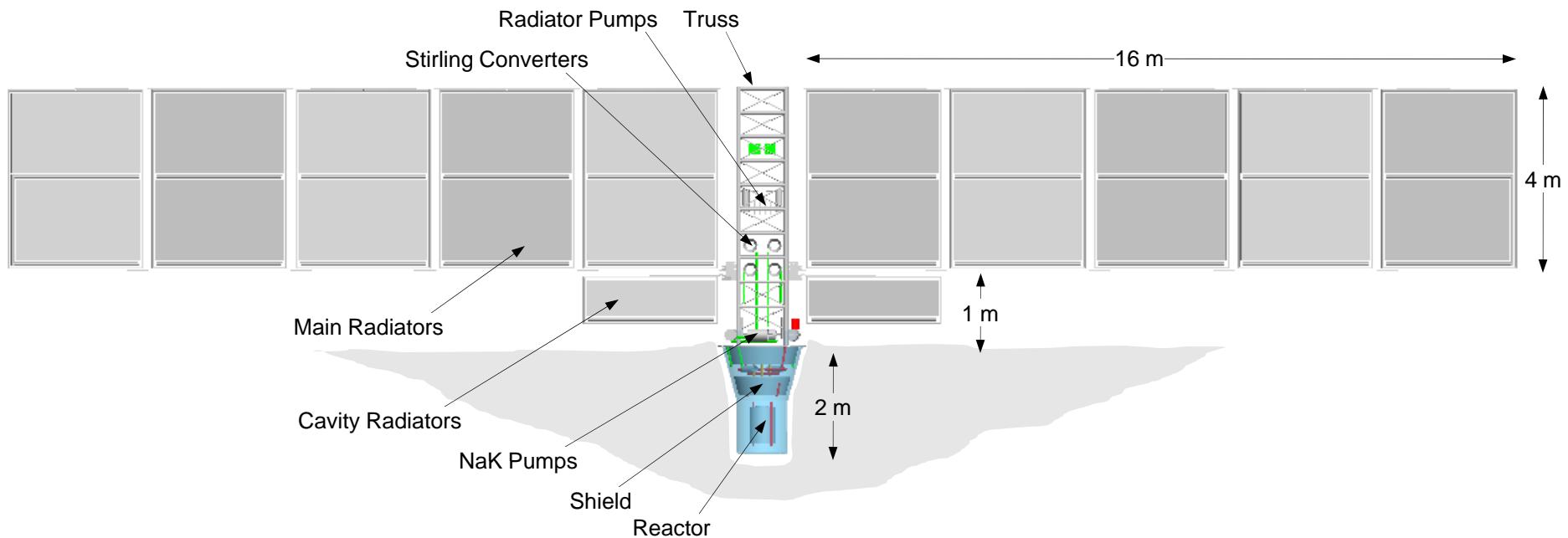
- **Abundant power to meet increasing mission demands:** scalable from kilowatts to megawatts and beyond
- **Potential for very high energy density and long life:** significant performance advantages compared to alternatives
- **Safe during all mission phases:** launched cold, remains subcritical until commanded startup, low residual radiation after shutdown
- **Operationally robust:** high reliability with capacity for contingency operations
- **Environmentally robust:** eliminates dependence on sunlight, resilient under adverse environments
- **Extremely flexible:** can be adapted to a wide range of mission applications using common technology building blocks
- **Affordable:** detailed studies show development costs are competitive with alternatives
- **Potential Terrestrial Spin-offs:** Low power, compact, autonomous reactors? Basic technologies?



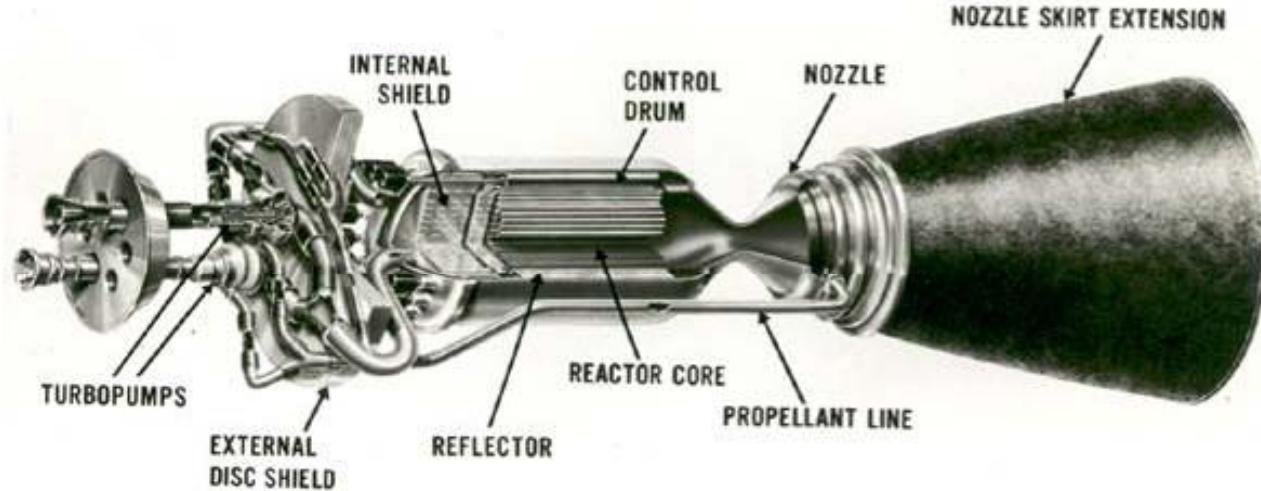


# Fission Surface Power Reference Concept

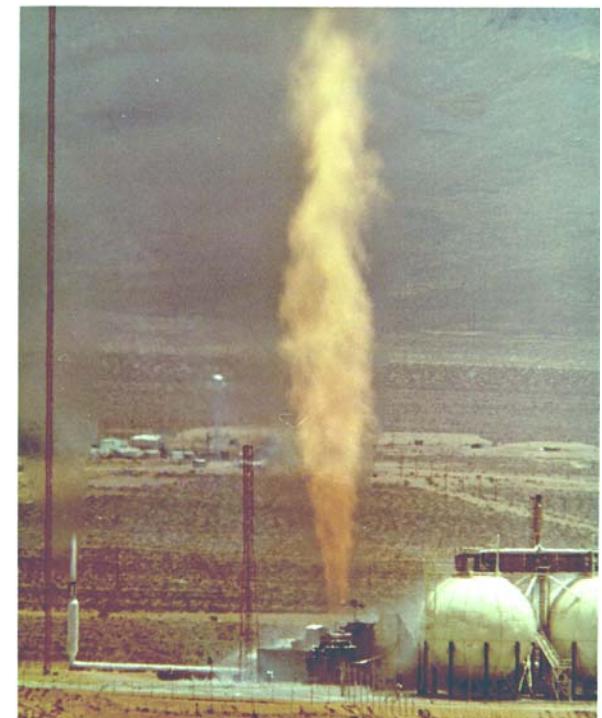
- Modular 40 kWe system with 8-year design life suitable for (global) lunar and Mars surface applications
- Emplaced configuration with regolith shielding augmentation permits near-outpost siting (<5 rem/yr at 100 m separation)
- Low temperature, low development risk, liquid-metal (NaK) cooled reactor with UO<sub>2</sub> fuel and stainless steel construction



# Nuclear Thermal Propulsion



- Hydrogen from propellant tank (not shown) directly heated by reactor and expanded through nozzle to provide thrust.
- ~850 second Isp demonstrated in ground tests at high thrust/weight.
- Potential for > 900 s Isp with advanced fuel forms and cycles.
- Potential Applications
  - Rapid robotic exploration missions throughout solar system
  - Piloted missions to moon, Mars, inner solar system





# Fission Power System Technology Project

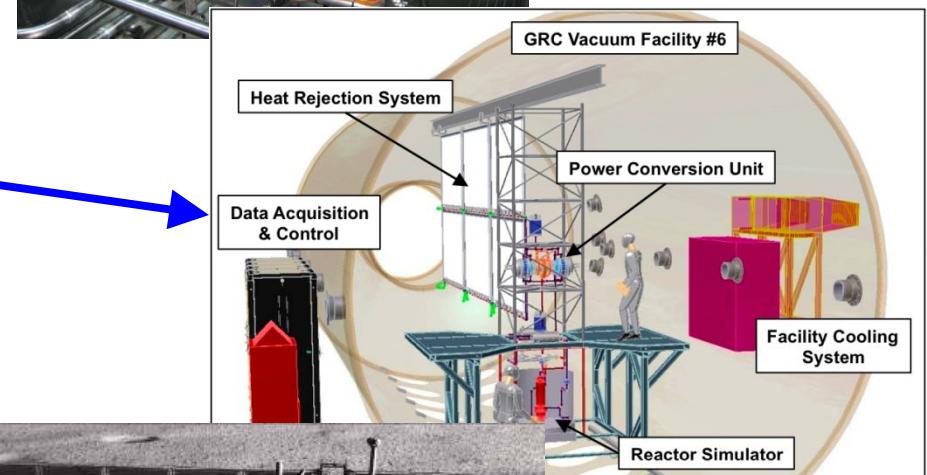
- Current FPS Project addresses mid-range Tech Readiness Levels:

- Sub-scale Pathfinder Component Tests
- Full-scale Technology Demonstration Unit (TDU) Integrated System Test
- Material & Component Irradiation Testing
- Concept Definition to support NASA Mission Studies

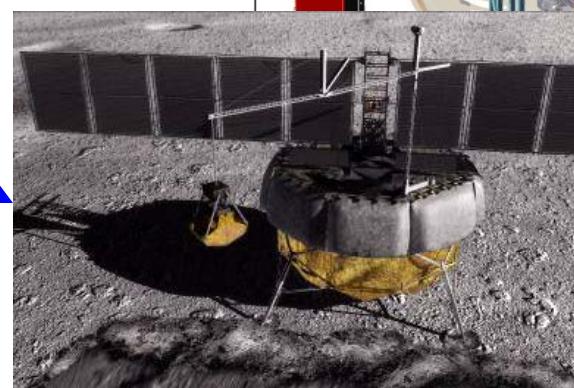
- Objective is Non-Nuclear TRL6 by 2014



2 kWe NaK-Stirling Demo



TDU System Test



LSS Scenario 5:  
Lander-Integrated  
FSP System

# Completed FPS Pathfinders



NaK Reactor Simulator



NaK Stirling Demo



Full-scale Radiator



Electromagnetic Pump



Direct Gas-Cooled Brayton



Full-scale NaK Pump Test



Pin Heater Demo



Titanium-Water Heat Pipes



Stirling PMAD Demo



Alternator Radiation Test



Reactor Control Drive



Radiator Demonstration Unit



High Power Dual Brayton



Feasibility Test Loop



Thermodynamically-Coupled Stirling

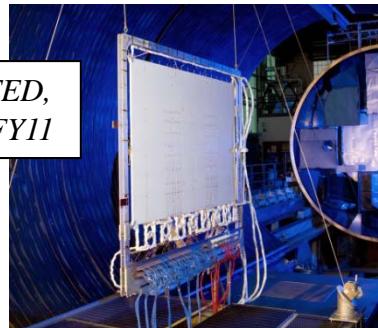
# Fission Technology Demonstration Unit

## Government, Industry, & Academia Team Effort



**Composite Heat Pipe Radiator – GRC & Industry**

*PROTOTYPE TESTED,  
TDU H/W RFP IN FY11*



*PROTOTYPE TESTED,  
TDU H/W IN FAB*



**NaK Volume Accumulator –  
OaK Ridge National Lab**

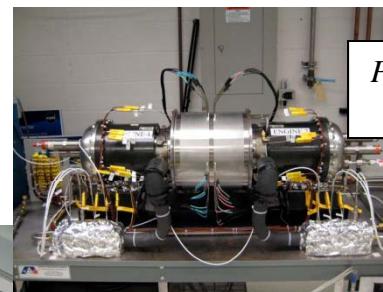
*PROTOTYPE TESTED,  
TDU H/W IN FAB*



**NaK Pump – Idaho National Lab**

**Stirling Power Conversion Unit – GRC & Sunpower**

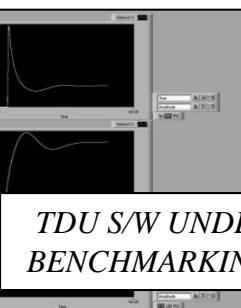
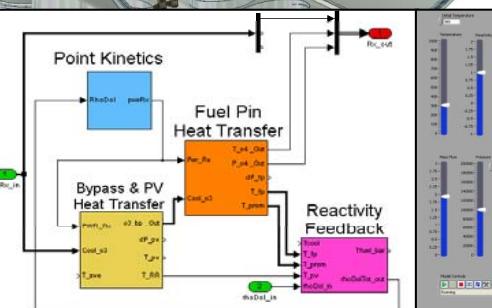
*PROTOTYPE TESTED,  
TDU H/W IN FAB*



**Core Simulator – MSFC &  
Los Alamos National Lab**



*PROTOTYPE TESTED,  
TDU H/W COMPLETED*



*TDU S/W UNDERGOING  
BENCHMARKING TRIALS*

**Reactor Simulation – Sandia National Lab**



## MSFC Early Flight Fission Test Facility (EFF-TF)

- Established in 1998, the MSFC Early Flight Fission Test Facility (EFF-TF) is designed to help enable affordable development of space fission systems.
- EFF-TF can perform highly realistic thermal hydraulic, heat transfer, structural, safety, and integrated system testing of space nuclear systems using non-nuclear (electrical) heat sources. Up to 8 MWe available power.
- Designed to test with any potential coolant. Heat pipe, gas cooled, and alkali metal cooled testing performed to date.
- Licensed for testing with natural and depleted uranium.



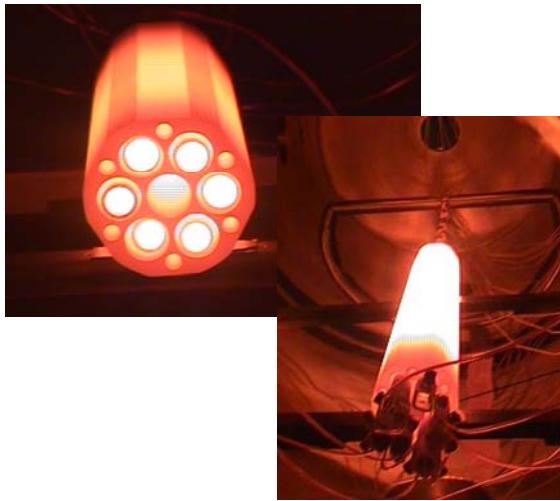
# Safe Affordable Fission Engine (SAFE)



LANL Design, Fast-Spectrum U-235, Ex-Core Control, Be Reflected, Primary Heat Transport via Heat Pipes

**Ultimate Goal: Perform realistic non-nuclear heated demonstrations of potential near-term space fission systems. Early focus is on core / heat exchanger.**

## Modular Unfueled Thermohydraulic Testing

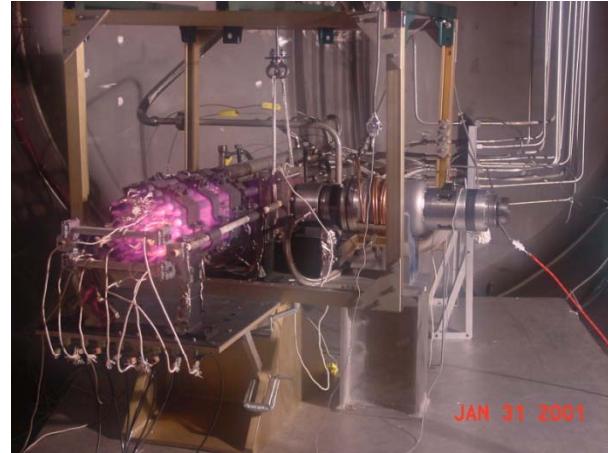


High-Temperature SAFE Module Testing Completed in FY00.

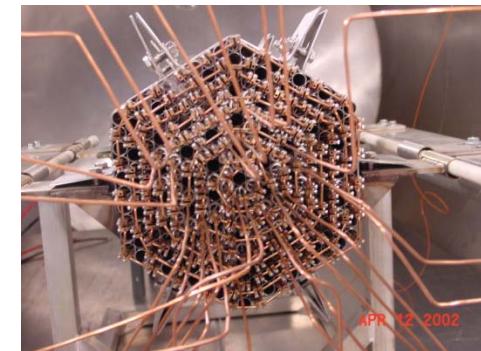
- > 1750 K Core Module Temperature.
- > 1450 K Heat pipe Temperature.
- Direct thermal propulsion mode demonstrated.
- Fast start of heat pipe (room temp to >1400 K in < 1 hr).
- Multiple heat pipe restarts.

## SAFE-30 End-to-End

- Average core temperature above 600 deg C in over 20 core tests including both vacuum and CO<sub>2</sub> environments.
- 10 operating heat pipes with an evaporator exit temperature ~ 650 deg C, > 17 kW measured transferred to the calorimeters.
- Core and Stirling engine integrated with ion engine and tested at JPL. Testing completed Sept 2002. Demonstrated integrated system with heat generated in fuel pins converted to high specific impulse thrust.



## SAFE-100



- Computationally and experimentally investigate prototypic module, core, and heat exchanger design for 100 kWt system
  - Module fabrication
  - Core support / expansion
  - Thermal performance
  - Thermal cycling effects
- Develop and utilize advanced instrumentation and power delivery system.
  - 32 radial control zones
  - Heaters match axial power profile
  - Coarse matching of fuel pin thermal conductivity
- Develop / utilize high purity liquid metal handling capability at NASA MSFC.

# Direct Drive Gas Cooled Reactor (DDG)



Sandia Design, Fast-Spectrum U-235, Ex-Core Control, Be Reflected, Primary Heat Transport via Noble Gas



37-Pin, 32-kWt  
subscale test

Pressure drop & flowing heat transfer code validation

Single module stagnant He/Xe decay heat code validation



133-Pin, 100 kWt  
subscale test

Pressure drop & flowing heat transfer code validation with radial power profile

Dynamics with 25-kWe Brayton turbomachinery and simulated nuclear temperature-dependent feedback, code validation

Multi-module stagnant He/Xe decay heat code validation



2 kWe  
BRU  
Test  
at  
NASA  
GRC

361-Pin, 400 kWt full-scale test

Full system pressure drop & flowing heat transfer code validation, radial power profile

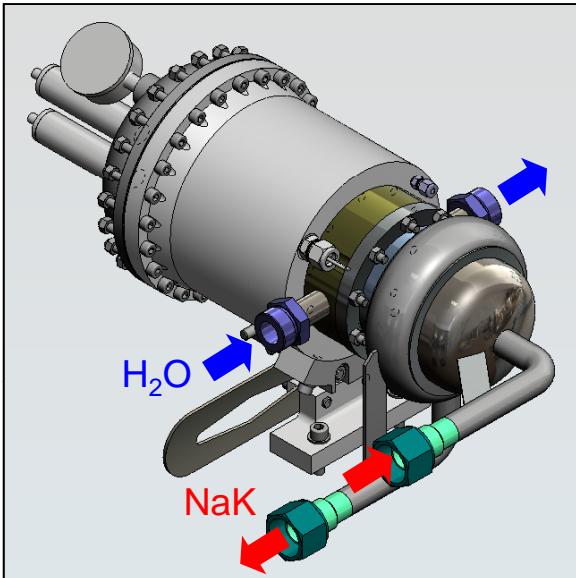
Full system dynamics with Brayton turbomachinery and simulated nuclear temperature-dependent feedback, code validation

Full system stagnant He/Xe decay heat code validation

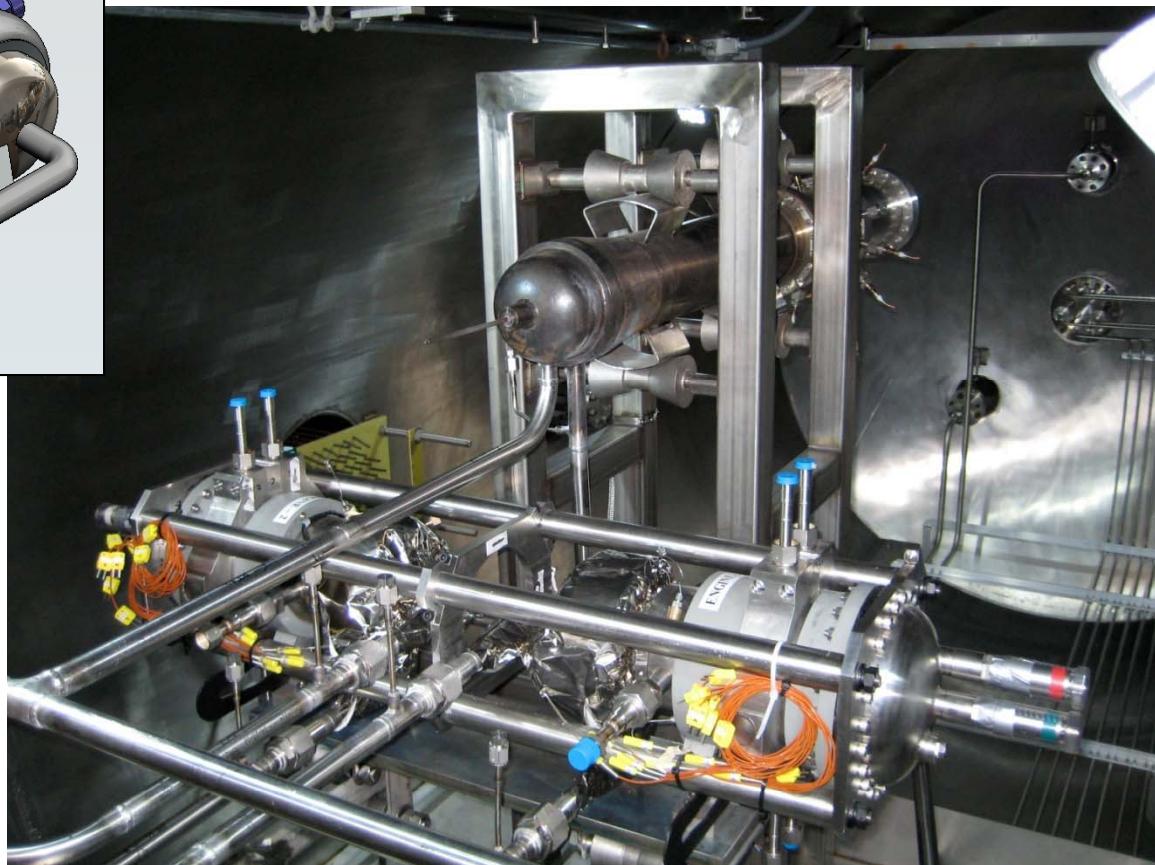


# 2 kWe NaK Stirling Demonstration Test

**Test Validated Reactor-Stirling  
Heat Transfer Approach for FSP  
(Stirling provided by NASA-GRC)**



- 2.4 kWe at  $T_{hot}=550^{\circ}\text{C}$ ,  $T_{cold}=50^{\circ}\text{C}$
- 32% Thermal Efficiency
- $<5^{\circ}\text{C}$  Circum. Gradient on Heater Head
- 41 Steady-State Test Points; 9 Transients
- 6 Reactivity Control Simulations



# Coupled NaK Loop / Stirling Test



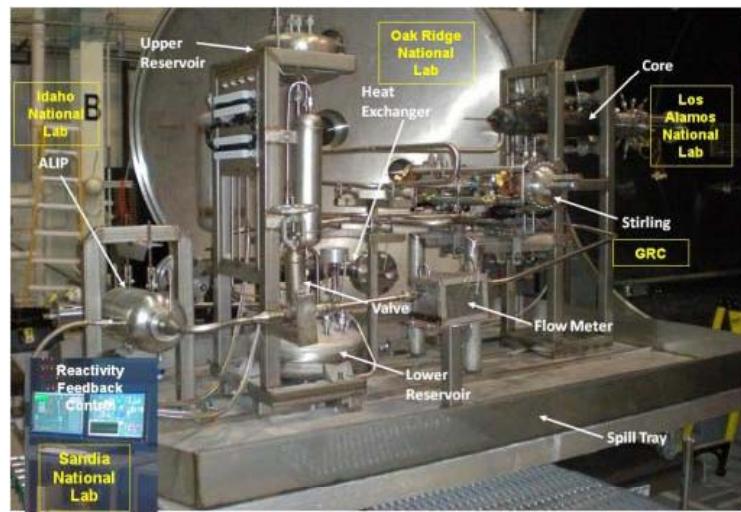
Cable tray providing protection from heat/NaK



Core Simulator Design by Los Alamos National Laboratory



Power Cable path to core



Integrated Stirling Test Assembly

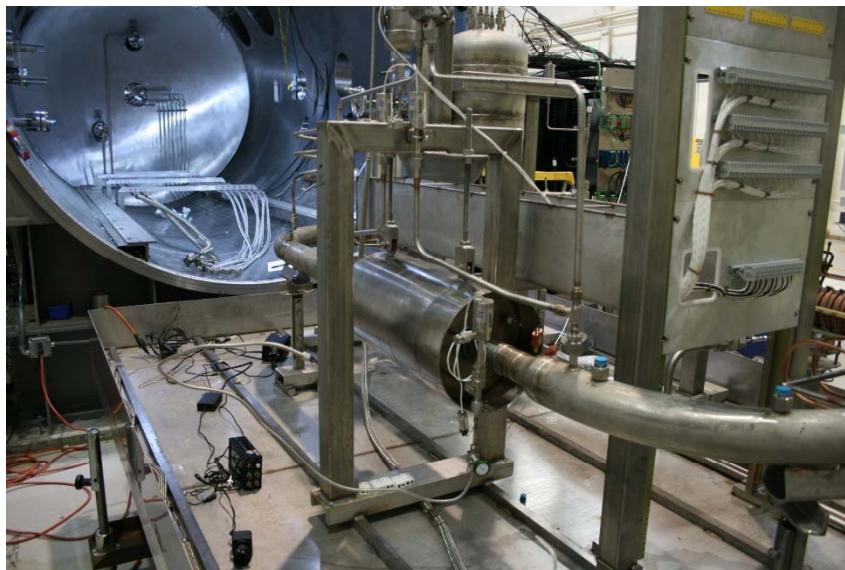


ALIP Provided By Idaho National Laboratory

# EFF-TF ALIP Test Circuit



Performance  
Mapping of Annular  
Linear Induction  
Pump (ALIP)  
provided by Idaho  
National Laboratory



# Performance Mapping of Annular Linear Induction Pump (ALIP) provided by Idaho National Laboratory



ALIP Test Circuit (ATC)



ALIP



ATC ready for chamber prior to NaK fill



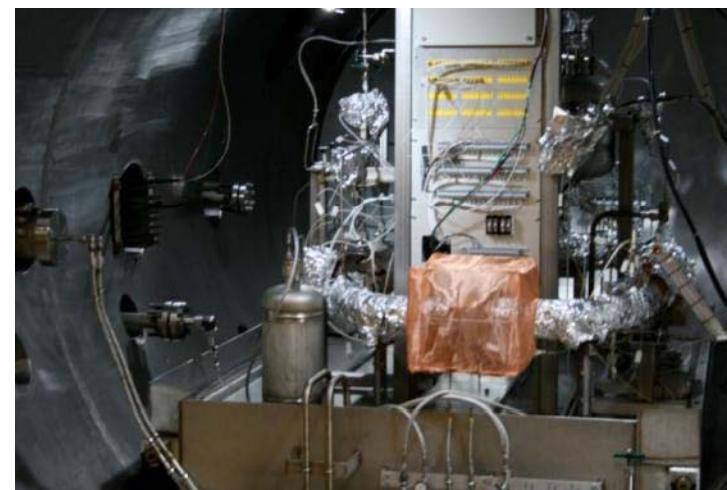
NaK fill



Enhanced heating assembly



Enhanced heating assembly ready for application of insulation



ATC Testing



# EFF-TF Feasibility Test Loop



## Feasibility Test Loop:

Investigate potential issues  
and optimizations related to  
pumped alkali metal systems

# Fission Surface Power – Primary Test Circuit (FSP-PTC)

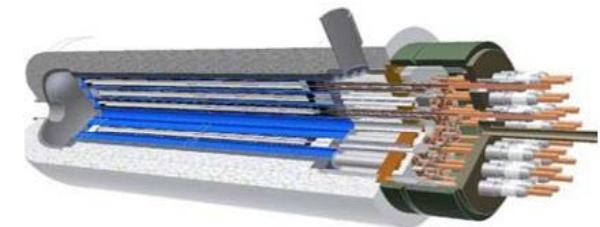
## 7 – Pin Reactor (Rx) Core Simulator Testing



MSFC  
Designed  
Advanced  
Simulators



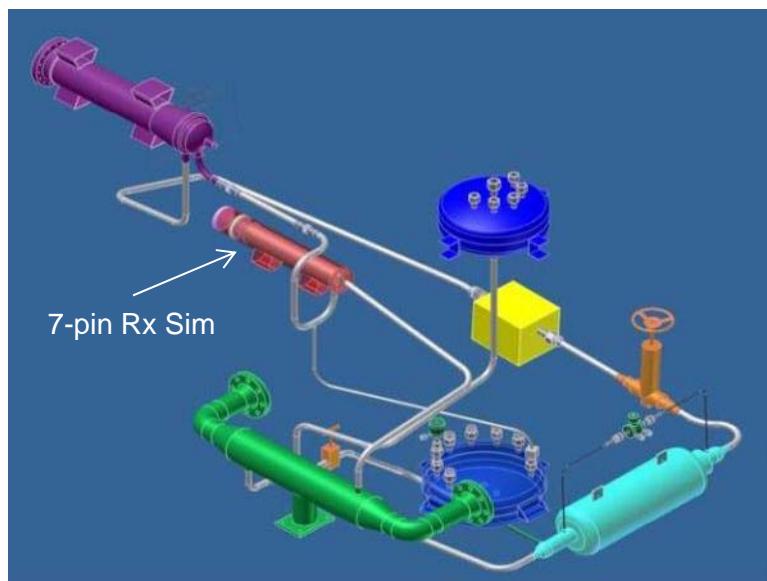
7-Pin Rx  
Core Sim



37 – Pin TDU Rx Core Sim



7 – Pin Rx Core Sim Rendering



Revised FSP-PTC layout for 7 – Pin Rx Core Sim



7 Pin Rx Core Sim installed in FSP-PTC

# FSPS Accomplishments



FSP-PTC  
Stirling &  
7 Pin Rx Core  
Sim  
Testing

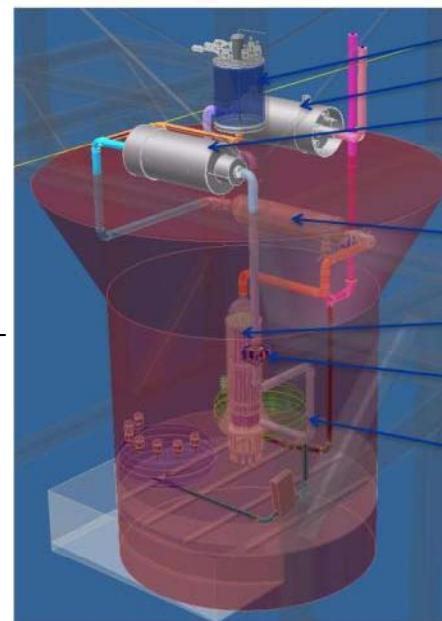


ATC  
Testing



FTL  
Testing

## Recent Activities Focused Towards TDU Reactor Simulator



Accumulator  
Intermediate Loop Pump  
Primary Loop Pump  
Intermediate Heat Exchanger  
Core  
Flow Meter  
Primary Loop Piping

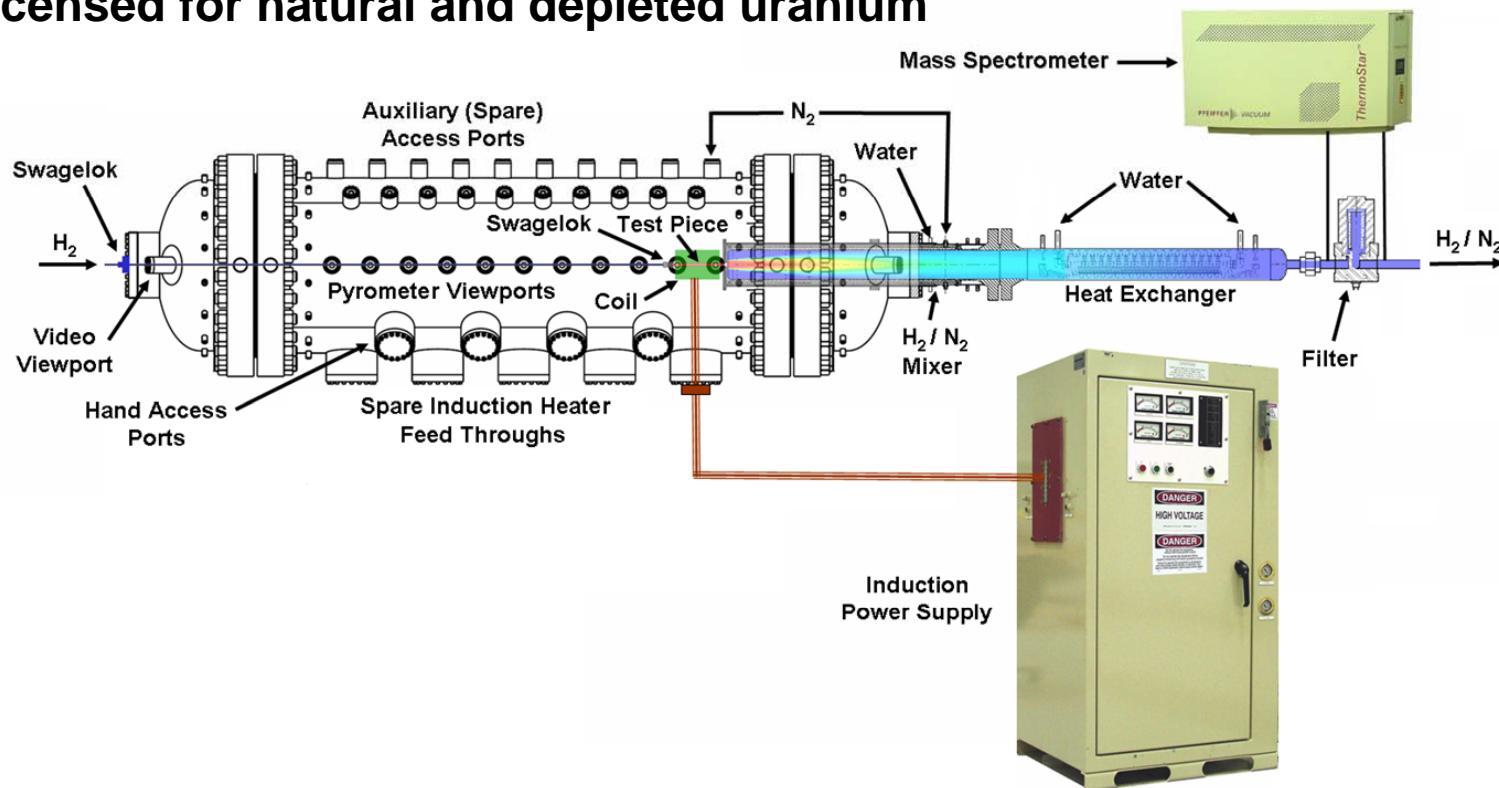
MSFC Designed Reactor Simulator in TDU  
(top view close up)

**MILESTONES**  
Fabricate & Test : 2010-2012  
Ship to GRC 2012

# Nuclear Thermal Rocket Element Environmental Simulator (NTREES)

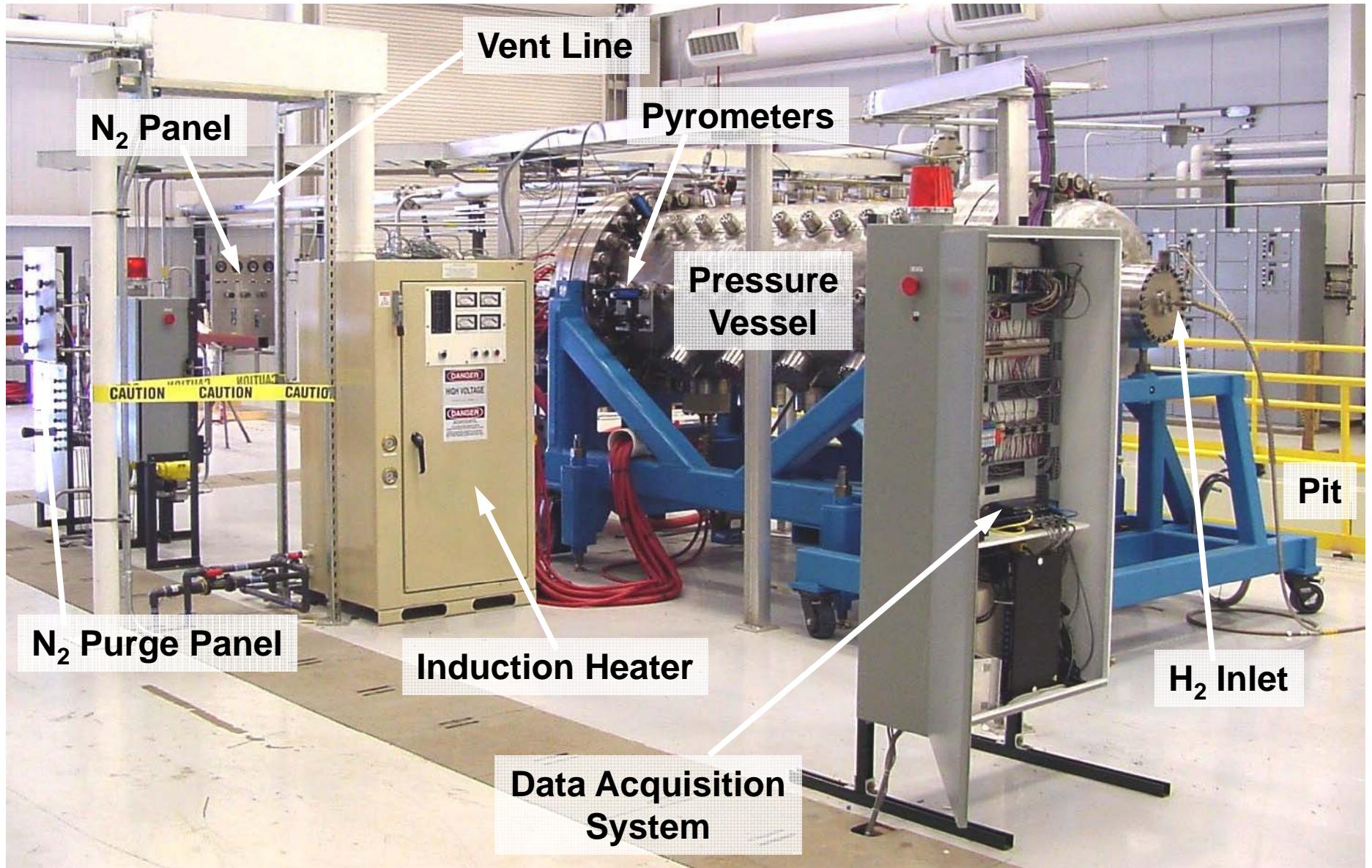


- 50 kW RF power supply (NTREES is sized to accommodate up to 5 MW of RF power)
- Exhaust mixer system and heat exchanger to cool and dilute hot hydrogen flow
- Backpressure control instrumentation, valves, and filters
- Mass spectrometer on vent gas system
- Pyrometers to measure test specimen surface temperatures
- Licensed for natural and depleted uranium





# NTREES Facility



# NTREES Type Testing: Advantages & Disadvantages

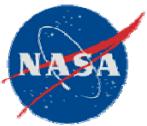


## Advantages

- Relatively easy to study behavior of fuel under conditions similar to that which would be encountered during actual engine operation
- Inexpensive (Thousands of \$/test)
- Quick turn around between tests (Days between tests)
- Many different fuel configurations may be tested
- Fuel is non-radioactive after test so fuel examination can be performed directly without special protective equipment

## Disadvantages

- Fuel is tested under similar, but not the exact conditions it will encounter during operation
- Simultaneous radiation, thermo-chemical, and thermal-hydraulic effects on fuel behavior will not be achieved
- Can only study one fuel element (or perhaps a small cluster of fuel elements) at a time



# Fuel Element Under Test in NTREES





## Near-Term Plans

- Complete Fission Power System (FPS) Technology Demonstration Unit (TDU) Component testing.
- Ship integrated TDU reactor simulator to GRC.
- Complete TDU testing at GRC.
- Complete NTREES upgrade to 1 MW.
- Complete NTREES testing of representative samples.
- Continue to investigate potential terrestrial spinoffs / applications of space nuclear power and propulsion technologies and test facilities.